Impacts of Ocean Waves on the Atmospheric Surface Layer: Simulations and Observations

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LONG-TERM GOALS

The long term objective of our research is to advance the understanding of air-sea interaction and the coupling between the atmospheric and oceanic boundary layers (the ABL and OBL) mediated by the surface gravity wave field, in order ultimately to develop better parameterizations of the boundary layers and surface fluxes for coupled, large-scale numerical models. Turbulence-resolving, large-eddy and direct numerical simulations (LES and DNS) are the main tools to be used to investigate interactions among the ABL, OBL, and the air-sea interface. Using numerically generated databases, we intend to investigate: (1) vertical heat and momentum fluxes carried by wave-correlated winds and currents; (2) enhanced small-scale, turbulent energy, mixing, and dissipation due both to enhanced wave-correlated wind and current shears and to wave breaking; and (3) wave-averaged influences due to mean Lagrangian currents (Stokes drift) that give rise to coherent Langmuir circulations in the ocean. These mechanisms will be considered for a variety of surface wave states. Finally, we intend to make an effort to connect our simulation results with the proposed Coupled Boundary Layers Air-Sea Transfer (CBLAST) field campaigns.

OBJECTIVES

Our recent research objectives have focused on understanding the interaction between imposed surface gravity waves and stratified turbulence in the atmospheric boundary layer. Specifically we are using LES to help interpret the observations collected from the Air-Sea Interaction Tower (ASIT) during the low-wind CBLAST field campaign.

APPROACH

We are investigating interactions among the ABL, OBL, and the connecting air-sea interface using both LES and DNS. The premise behind this approach is that the fundamental processes that lead to air-sea coupling will manifest themselves in three-dimensional, time-dependent simulations. The capabilities of the LES code used here are documented in Moeng (1984), Sullivan

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et al. (1994), Sullivan *et al.* (1996), McWilliams *et al.* (1997), and Sullivan *et al.* (2004). A companion DNS code that accommodates a temporal and spatial varying lower boundary utilizing a co-located grid architecture is described in Sullivan *et al.* (2000) and Sullivan & McWilliams (2002). We are collaborating with James Edson (U. Conn.) and Tihomir Hristov (Johns Hopkins U.) using observational periods from CBLAST that feature light winds and strong swell to validate and compare with our LES solutions.

WORK COMPLETED

The goal of our computational work is to use simulation results to examine the interactions between winds and waves in the ABL, and in particular to aid in the interpretation of observations obtained during the CBLAST field campaigns. With this perspective, we continued to analyze our previous LES solutions for turbulent flow above fast moving waves and extended our database to include a wider range of atmospheric stability and wind-wave orientations. LESs with waves propagating against the wind were performed using the same input parameters as our previous LES for winds following swell: computational domain $(1200 \times 1200 \times 800)$m with grid resolution $(250 \times 250 \times 96)$ gridpoints using smoothly varying stretched vertical grids; geostrophic winds $U_g = 5\text{ms}^{-1}$ and surface roughness $z_o = 2 \times 10^{-4}$m; and an imposed surface wave with waveslope $ak = 0.1$, phase speed $c = 12.5\text{ms}^{-1}$, and wavelength $\lambda = 100$m. Simulations were performed using a parallel, surface-wave resolving code (Sullivan *et al.* 2004). Because of the large value of c, small horizontal grid spacing $\triangle x \sim 4.8$m, and small time-step $\triangle t \sim 0.3$s the simulations required about 70,000 time-steps (approximately 10 large eddy turnover times) which consumes about 2800 CPU hours on an IBM SP4+.

Observational data was collected from the ASIT using a variety of sensors deployed in the air and water. For the research described here we focus on the turbulence data gathered from 4 3-D sonic anemometers mounted at nominal heights $z = (5.85, 7.94, 11.8, 18.1)$m above the water. Wave height information was obtained from a microwave TSK sensor while directional spectra were deduced from underwater current meters. During CBLAST Low a wide variety of atmospheric conditions and wave states were encountered with the bulk of the conditions governed by light winds and seas dominated by swell. More than 500 hundred hours of turbulence flux and wave height data were analyzed. Eddy correlation was used to estimate turbulent momentum and heat fluxes $(u'w', \theta'w')$ from the measured time series of (u, v, w, θ) with the averaging period 30 minutes in duration. Fuller descriptions of the CBLAST Low campaign are reported by Edson *et al.* (2006a,b).

In related efforts, we continue to analyze observational data obtained from the field campaign OHATS (Ocean Horizontal Array Turbulence Study) with the objective of identifying light-wind conditions with wave effects to validate the predictions of the LES. The OHATS and CBLAST low-wind databases are complimentary: the field site for OHATS was identical to the CBLAST low-wind campaign and also used the ASIT. During CBLAST and OHATS the surface winds are generally $\sim 5\text{ms}^{-1}$ and the wave fields are frequently dominated by 100m swell generated by distant fronts. Thus the winds and waves are often in a non-equilibrium state. Further information about the objectives of and results from OHATS can be found in the report by Sullivan *et al.* (2005a) and at web sites
http://www.atd.ucar.edu/rtf/projects/OHATS04/ and
http://www.whoi.edu/science/AOPE/dept/OHATS/intro.html.

Also we continued our efforts to examine the interactions between stochastic breaking waves, Stokes drift, and currents in the OBL. A goal of this research is to compare OBL mixing with and without surface wave effects. We find that turbulent mixing in the OBL depends on both the wave height and breaker spectra, with the coupling between breaking and Stokes drift more important for young seas. Efforts from this work are described in a recently submitted publication, Sullivan *et al.* (2006).

RESULTS

LES profiles of mean and turbulent variables above swell show significant differences compared with rough wall boundary layers and flow over hills (*i.e.,* stationary waves). Our interpretation suggests that this results from momentum flux divergence which accelerates the flow and a retarding pressure gradient both of which are opposite to the momentum balance in classical boundary layers. LES also predicts that well organized surface waves impact both the instantaneous and net vertical momentum flux in the PBL. Waves leave their imprint on the coherent flux carrying structures as illustrated in figure 1. Here we compare cases with the same large scale forcing and surface roughness but varying wave fields; no waves, waves propagating with the wind, and waves propagating against the wind. Inspection of the flow visualization at a height of $z = 20$m shows a dramatic response of the PBL. Over a flat lower boundary the bulk of the vertical momentum flux is carried by a few sparsely distributed structures elongated in the mean wind direction. Fast moving swell propagating with or against the wind destroys the coherence of these streaky near wall structures. For winds following waves, the momentum flux structures in the surface layer are weak and carry slightly positive flux. This is in sharp contrast to the situation of waves propagating against the wind which generates vigorous momentum flux of both signs (see panel c) of figure 1). $u'w'$ induced by the waves remains coherent well above the surface layer and appears to interact with the background PBL turbulence. In this situation the net momentum flux is negative and its fluctuating value noticeably exceeds its mean value.

The computational results provide motivation to search for wave influences in measured wind fields from the CBLAST field campaign. Compared to a fully developed sea, the wave fields in the LES are highly idealized, *e.g.,* they do not include multi-components, three-dimensionality, and time varying wave amplitudes and phases. Hence, we expect wave influences to be more subtle and difficult to isolate in observations. A statistical measure we find useful to help identify wave effects is a quadrant analysis of the vertical momentum flux. This technique, first used by Antonia & Chambers (1980) separates the turbulent momentum flux $u' w'$ into four categories (quadrants) according to the sign of the two fluctuating velocity components (see figure 2).

In the surface layer of a rough wall boundary layer the net (average) momentum flux $\langle u' w' \rangle < 0$ and is dominated by sweeps and ejections associated with motions in quadrants Q2 and Q4. Positive flux contributions from quadrants Q1 and Q3 are less frequent and weaker in magnitude. We performed a quadrant analysis of the vertical momentum flux in the marine surface layer using CBLAST data with the expectation that the influence of swell would appear at sufficiently high wave age. The results of the analysis are displayed in figure 3 where we show the (normalized) ratio of negative to positive momentum flux quadrants $Q_r = -(Q2+Q4)/(Q1+Q3)$ for varying wave age c_p/U_a. Observational results for flow over stationary roughness (Sullivan *et al.* 2003) are also depicted for comparison. A wide range of atmospheric stratification is considered but the results are restricted to situations where the winds and waves are aligned within ± 30 degrees. The results contain scatter but the quadrant flux ratio clearly shows wave influences, a distinct downward trend for increasing wave age $c_p/U_a > 1$. Our interpretation, based on our LES results, is that the fast moving components of the wave field enhance the upward momentum transport from the ocean to the atmosphere and this momentum appears in the positively signed flux quadrants $(Q1, Q3)$. At a sufficiently large wave age a near balance between negative and positive flux contributions is achieved. This result is quite similar to the predictions from our direct numerical simulations (Sullivan *et al.* 2000) and from LES (see figure 1). Notice also that the effects of fast moving waves on momentum transport are not confined to the first measurement level $z = 5.85$m but appear to extend over the bulk of the surface layer, up to at least $z = 18.1$m. The observations from Smedman *et al.*(1999) also follow a similar trend with wave age.

The present results can be used to help interpret the observations of bulk air-sea fluxes. The measurements of the neutral drag coefficient C_D obtained during CBLAST Low (see figure 4) agree well with the TOGA-COARE algorithm (Fairall *et al.* 2003, Edson *et al.* 2006a) over a wide range of wind speeds. The greatest discrepancy (and variability) occurs at low winds where the measured values of C_D can be either positive or negative with amplitudes exceeding the average estimate by a factor of two or more. At low winds, say $U_a < 5\text{ms}^{-1}$, LES predicts swell induces a significant change in the vertical momentum flux. Swell propagating with the winds reduces the observed momentum flux (or even changes its sign) while the same swell propagating counter to the winds greatly enhances the surface drag. The model predictions suggest that the impact of non-equilibrium seas can cause large variability in measured drag coefficients at low winds. This effect is not considered in the TOGA COARE algorithm (Fairall *et al.* 2003).

The current LES with its monochromatic wave represents an idealization of a light wind PBL with swell. In the open ocean, a multi-component wave field can simultaneously be a sink and source of momentum for the atmosphere, with short (long) waves extracting (imparting) momentum. The sign and magnitude of the near surface fluxes will then depend on several factors including the orientation of winds and waves and the relative location of the wave spectral peak and the mean wind. Flux parameterizations thus require information about the wave field in addition to the winds.

IMPACT/APPLICATIONS

LESs of atmospheric turbulence over fast moving surface waves predict the formation of a low-level jet, positive momentum flux, and compare favorably with the surface layer results from the observations collected during CBLAST Low. At low winds winds and waves are often in disequilibrium and then wave state influences the momentum flux. Hence, Monin-Obukhov similarity theory is insufficient to describe marine surface layers in the presence of fast propagating swell.

TRANSITIONS & RELATED PROJECTS

We are currently engaged in analyzing data collected during the Ocean Horizontal Array Turbulence Study (OHATS). This is a joint effort between NCAR, Woods Hole Oceanographic Institute, and Pennsylvania State University. The goal of OHATS is to gather data about the impact of surface waves on subgrid-scale variables that are modeled in LES codes. The measurement technology and analysis will be similar to that employed in the land-based Horizontal Array Turbulence Study (HATS) described in Sullivan *et al.* (2003) and Horst *et al.* (2004).

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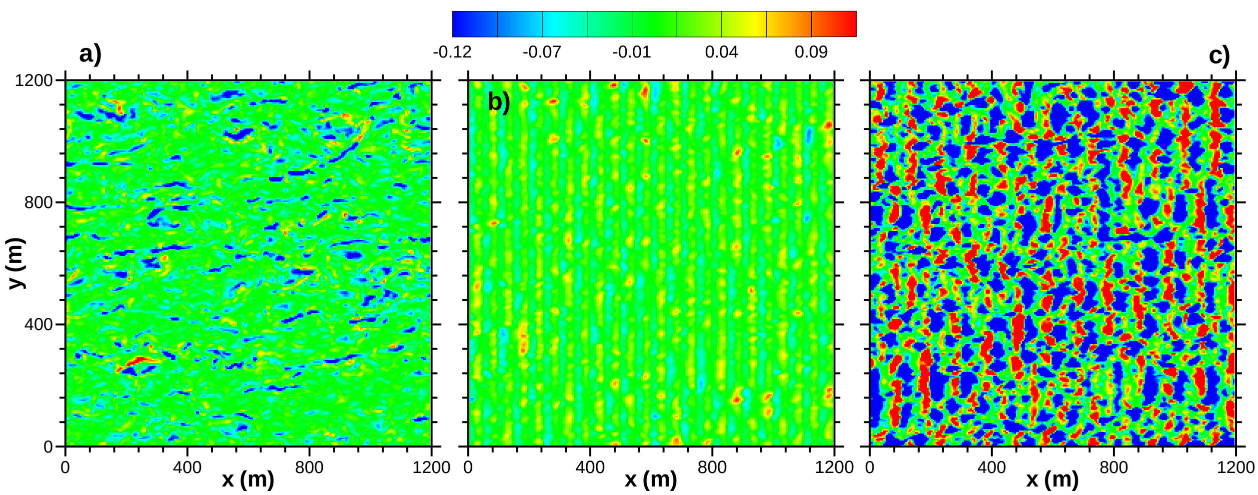

Figure 1: Instantaneous vertical momentum flux $u'w'$ from LES at a height $z = 20$m above the water. Panel a) is turbulent flow over parameterized roughness $z_o = 0.0002$m and no surface waves. Panel b) is flow over swell traveling with the wind and c) is flow over swell traveling against the wind. The wave conditions are phase speed $c = 12.5$ms^{-1}, wavelength $\lambda = 100$m and waveslope $ak = 0.1$. The color bar for momentum flux is in units of (ms^{-1})^2.

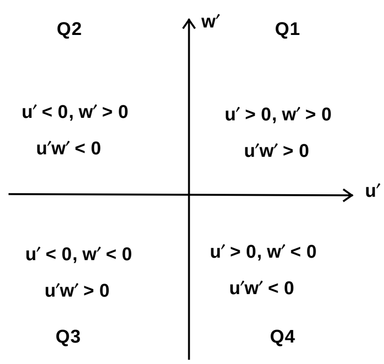

Figure 2: Decomposition of the vertical momentum flux into quadrants (Q1, Q2, Q3, Q4) based on the sign of the fluctuating horizontal and vertical velocity (u', w').

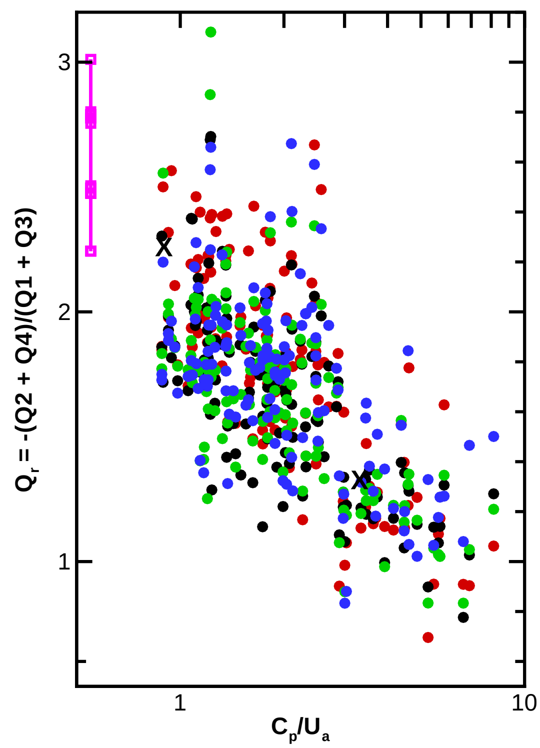

Figure 3: Quadrant analysis of the vertical momentum flux in the marine surface layer for varying wave age from CBLAST Low. Solid circles are measurements at z =(5.85 •, 7.94 •, 11.8 •, 18.1 •)m. The observations of Smedman *et al.*(1999) are denoted by X and results for flow over stationary roughness (note wave age = 0) Sullivan *et al.*(2003) are indicated by pink squares. Note for $Q_r \leq 1$ the net drag $(Q_1 + Q_2 + Q_3 + Q_4)$ is less than zero as shown in figure 4.

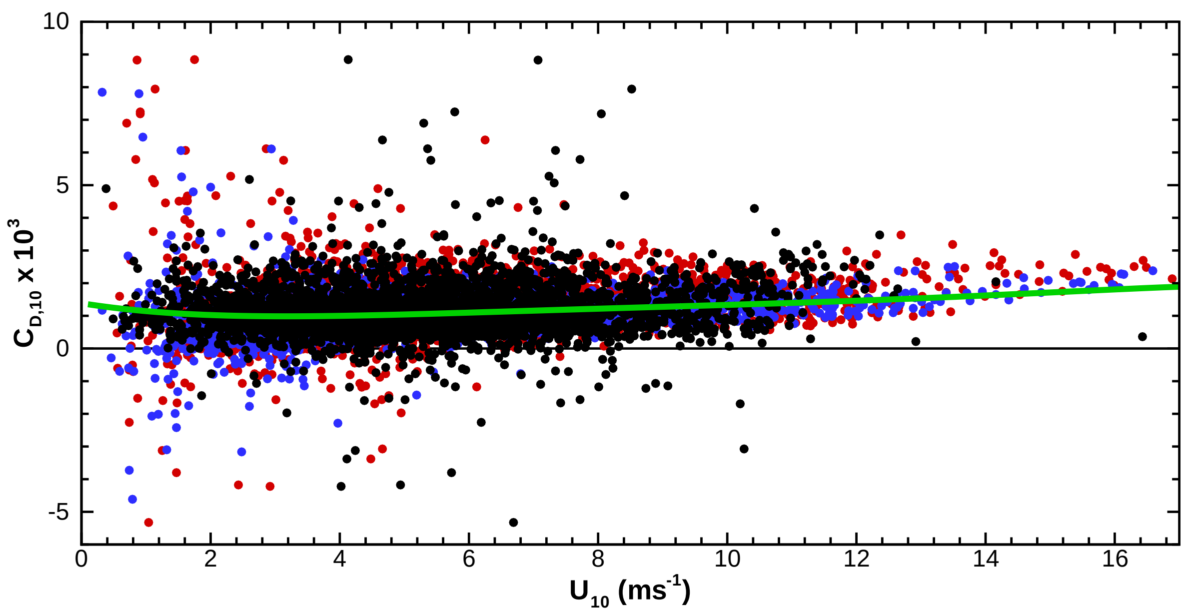

Figure 4: Drag coefficients obtained from three measurement levels during CBLAST Low Edson *et al.*(2006). C_D is referenced to a 10m height and neutral conditions. The TOGA COARE 3.0 parameterization is indicated by the solid green line. Note the negative values of C_D and increase in variability at low winds which is a signature of a swell dominated surface layer.